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Short communication

Method for evoking a trip-like response using a treadmill-based perturbation during locomotion

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ABSTRACT

Because trip-related falls account for a significant proportion of falls by patients with amputations and older adults, the ability to repeatedly and reliably simulate a trip or evoke a trip-like response in a laboratory setting has potential utility as a tool to assess trip-related fall risk and as a training tool to reduce fall risk. This paper describes a treadmill-based method for delivering postural perturbations during locomotion to evoke a trip-like response and serve as a surrogate for an overground trip. Subjects walked at a normalized velocity in a Computer Assisted Rehabilitation Environment (CAREN). During single-limb stance, the treadmill belt speed was rapidly changed, thereby requiring the subject to perform a compensatory stepping response to avoid falling. Peak trunk flexion angle and peak trunk flexion velocity during the initial compensatory step following the perturbation were smaller for responses associated with recoveries compared to those associated with falls. These key fall prediction variables were consistent with the outcomes observed for laboratory-induced trips of older adults. This perturbation technique also demonstrated that this method of repeated but randomly delivered perturbations can evoke consistent, within-subject responses.

1. Introduction

Research on falls is increasingly important since falls are the leading cause of unintentional-injuries leading to death for the rapidly growing population of older adults in the United States (Centers for Disease Control and Prevention, 2013). As important, persons with lower limb amputation have a high incidence of falls. More than 50% of individuals with lower limb amputation fall annually (Miller et al., 2001), compared with a fall prevalence of 33% generally associated with older adults. Falls can lead to detrimental consequences such as loss of confidence, fear of falling, and injury. It is therefore important to find a way to assess the ability of these persons to recover from a large postural perturbation and find methods for training them to avoid a fall before injury occurs.

Only a handful of research studies have utilized novel methods to induce a laboratory trip during locomotion. These include an obstacle rising above the ground to obstruct the swing foot motion (Eng et al., 1994; Pavol et al., 1999; Pijnappels et al., 2004), restricting the swing foot motion using a cord or similar device (Blumentritt et al., 2009; Krasovsky et al., 2012; Smeesters et al., 2001), or dropping an obstacle on a treadmill to obstruct the swing leg forward movement (Schillings et al., 1996). These methods successfully induce a realistic trip, but repeated trips can be anticipated. In contrast, disturbances delivered by a computer-controlled treadmill system may offer an easily controlled and reproducible alternative. In this paper, we describe a method of delivering an unanticipated perturbation to subjects walking on a treadmill that evokes a repeatable recovery response that requires a compensatory stepping response to avoid falling.

2. Methods

Participants were active-duty members of the U.S. military with traumatic unilateral lower limb amputation who were recruited from the Comprehensive Combat and Complex Casualty Care program at the Naval Medical Center San Diego (NMCSD). In this study 12 male subjects (mean age: 24.3 ± 2.8 years, weight: 77.0 ± 14.3 kg, height: 177.5 ± 6.5 cm, and time since amputation: 25 ± 31 months) participated. Subjects were between 5 and 114 months post-amputation and highly functional (Medicare Functional Classification Level K3 or K4). Inclusion criteria were traumatic transtibial amputation, male, between the ages of 18 and 40 years

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Fig. 1. Subject walking within the Computer Assisted Rehabilitation Environment (CAREN) at the Naval Health Research Center.

who were ambulating without an assistive device, medically cleared for high-level functional activities, and could walk continuously for more than 15 min. Exclusion criteria for subjects included traumatic brain injury, vestibular dysfunction, and significant injury to the sound limb. The experimental protocol was approved by the NMCSD, Naval Health Research Center (NHRC), and Mayo Clinic institutional review boards as well as the Human Research Protection Office, U.S. Army Medical Research and Materiel Command. Subjects provided written informed consent prior to participating in the study.

Perturbations were delivered while subjects walked in a Computer Assisted Rehabilitation Environment (CAREN) extended version (Motek Medical BV, Amsterdam, The Netherlands). This immersive virtual environment consists of a six degrees of freedom motion platform (Moog Inc., East Aurora, New York) with a 1.7-m-long dual-belt (side-by-side) instrumented treadmill (Forcelink, B.V., Culemborg, The Netherlands) capable of high accelerations (up to 5 m/s^2). Visual inputs were synchronized with the subject's treadmill walking speed to simulate walking on an endless pastoral path (Fig. 1). The normalized walking speed for each subject was controlled for leg length and set at the Froude number (Fr) 0.2, where $Fr = v^2/gl$, v is the walking speed, g is the gravitational constant, and l is the leg length (Alexander, 1989). The selection of this speed was based on the overground self-selected walking speed of subjects with lower limb amputation previously studied at the NMCSD Motion Analysis Laboratory, and it was chosen to be slightly slower than self-selected walking velocity so that the subjects could maintain a constant speed for the duration of the perturbation trial (approximately 15 min) without fatigue. Walking speeds ranged from 1.0 to 1.5 m/s.

Each subject wore a full-body harness tethered to an instrumented safety system (Interface, Scottsdale, AZ) that could support the subject's full weight. The length of the tether was set so that, in the event of a fall, the subject's hands and knees would not contact the ground. The tether did not interfere with normal walking. A trial was categorized as a fall if more than 50% of the subject's body weight was supported by the safety harness (Brady et al., 2000). In addition, a trial was categorized as a fall if the rear (stance) foot triggered the rear safety light gate causing the treadmill belt motion to stop (treadmill length is 1.7 m). Trials where the harness supported 20–50% of body weight were classified as harness assisted and were not included in the analyses. In addition, trials during which the stepping response caused the subject to step sideways off of the treadmill were excluded from the analysis.

Each subject first walked for 10 min at the normalized walking speed in order to become acquainted with treadmill locomotion. This warm-up period was followed by a 6-min walk at the same speed during which six perturbations, three each for the prosthetic side and sound side limbs, were delivered at random times to evoke a trip-like response. Initiation of the perturbation profile was triggered when initial contact of the selected foot and a force of 40 N was detected by the underlying force plate. The perturbation profile was defined by a series of changes in treadmill velocity (Fig. 2) and began with the treadmill decelerating (-15 m/s^2) from the normalized walking velocity for 50 ms, followed by a treadmill acceleration (15 m/s^2) for 270 ms. This temporarily brought the treadmill to a velocity between 4.3 and 4.8 m/s (depending on the subject's normalized walking speed) before decelerating (-15 m/s^2) back to the normalized walking speed. Both belts moved at the same speed throughout the perturbation. The elapsed time of the perturbation was less than a second. The timing of these changes in velocity was chosen so that, during the second phase of the perturbation (treadmill acceleration) the foot selected to be perturbed was in stance and the contralateral limb was in swing (usually at midswing half way through phase 2). The initial deceleration phase helped to arrest the velocity of the stance foot while allowing the trunk to continue forward, thereby increasing the dynamic stability margin (Hof et al., 2005) and making the recovery response during the acceleration phase more

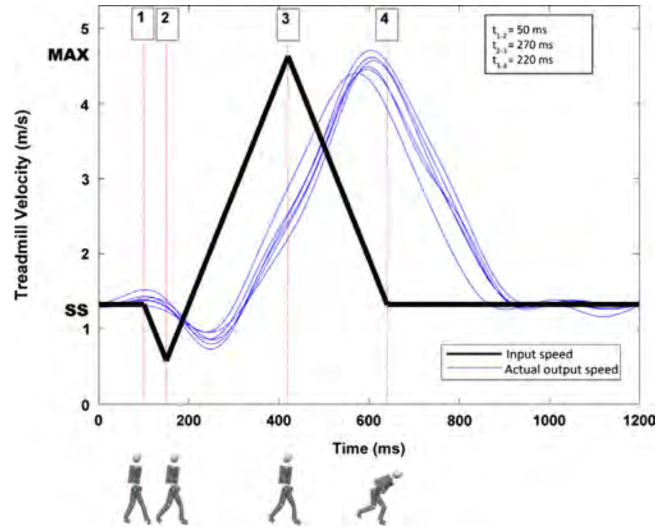

Fig. 2. Perturbation timing and velocity profile utilized to perturb subjects on the treadmill during gait. The four vertical time points mark where a change in the treadmill velocity occurred and figures below the graph show the approximate position of the subject at this time point. Thick line indicates the input speed sent to the treadmill. Thinner lines illustrate the actual output speed of the treadmill for several trials, showing the variability of the signal. SS is the steady state speed, which ranged from 1.0 to 1.5 m/s for the participating subjects.

challenging. The limb that was on the ground (stance limb) during the treadmill acceleration is described as the perturbed limb in this paper.

The subject was instructed to recover from the perturbation as best he could and continue walking if possible. If the subject fell, the treadmill was stopped and the subject was allowed to rest, if desired, before continuing the protocol. If the subject was able to fully recover, he continued walking at the normalized velocity until another perturbation was delivered or data collection was complete.

For the study, 34 retroreflective markers were placed on the subject using a modified Helen Hayes marker set configuration (Kadaba et al., 1990). The motion of the markers was tracked using a 12-camera motion capture system (Motion Analysis Corporation, Santa Rosa, CA, USA) operating at 120 Hz. Marker data were filtered using a fourth-order bidirectional recursive Butterworth filter with a cutoff frequency of 9 Hz in Visual3D (C-Motion, Inc., Germantown, MD, USA). A 13-segment rigid body model using the marker data was created to represent the whole body. Trunk flexion angle, defined as the angle of the trunk segment with respect to vertical, was calculated from time of the perturbation to initial recovery step. Trunk flexion velocity was computed as the derivative of the trunk flexion angle. Root mean square (RMS) error of trunk flexion angle and velocity were calculated for the second and third trips on each side.

A one way ANOVA was used to compare peak trunk flexion angle and peak trunk flexion velocity during the perturbation between trials that were classified as a fall to those outcomes that were classified as a recovery on the prosthetic limb (no falls occurred during the sound limb trials). A one way ANOVA was also run to compare the difference in peak trunk flexion angle and velocity between the sound and prosthetic limb recovery (non-fall) trials. Statistical tests were performed using SPSS 18 (IBM Corporation, Armonk, NY, USA) and statistical significance was set at $p \leq 0.05$.

3. Results

The perturbation protocol was successfully completed by 12 subjects. Four of the 12 subjects experienced a fall during the induced perturbation, with the fall occurring during the initial perturbation on the prosthetic side limb. Two of these four subjects fell again during the second perturbation on the same side. Three subjects experienced a harness assist trial, two on the prosthetic side limb and one on the sound side limb. In total, of the 72 cumulative perturbations from all the subjects, 63 trials were classified as a successful recovery, three were classified as a harness assist, and six were classified as a fall, with all of the falls occurring when the prosthetic side limb was perturbed.

For perturbations on the prosthetic side limb (i.e. the prosthetic limb is on the ground when the treadmill perturbation begins), mean peak trunk flexion angles associated with recoveries ($31 \pm 12^{\circ}$) were

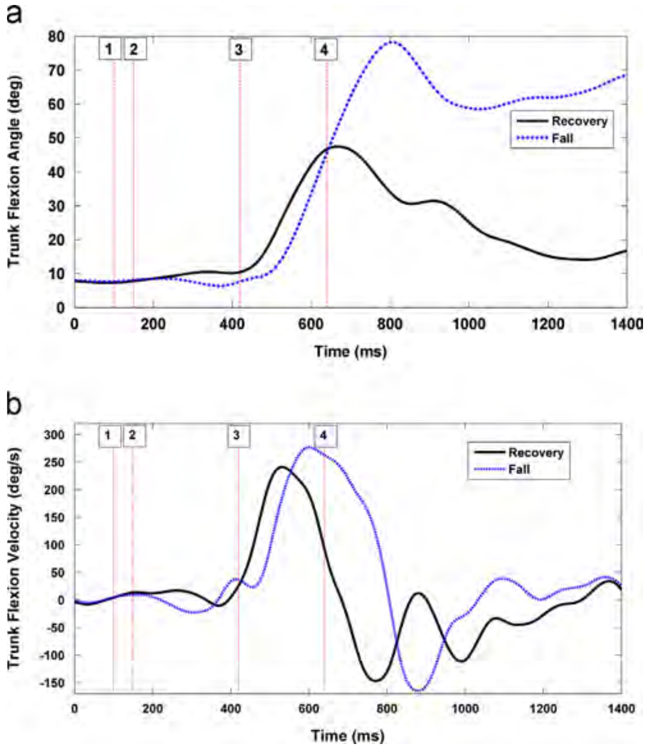

Fig. 3. Difference in (a) trunk flexion angle and (b) trunk flexion velocity between a fall and a recovery for a perturbation of the prosthetic side limb (limb on the ground during the perturbation). The boxed numbers refer to time points in the perturbation profile as described in Fig. 2.

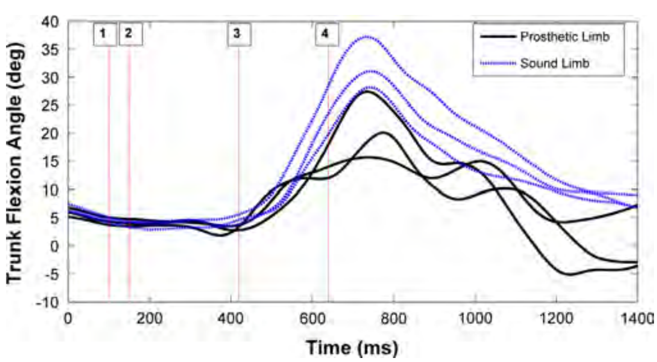

Fig. 4. Trunk flexion angle – consistency in response for a representative subject recovering from perturbations of the prosthetic (solid lines) and sound limb (dashed lines). The limb on the ground (stance limb) during the treadmill perturbation is described as the perturbed limb.

significantly smaller ($p < 0.001$) than those associated with falls ($62 \pm 23°$) (Fig. 3a). Similarly peak trunk flexion velocities during recoveries (139 ± 57 deg/s) were significantly slower ($p < 0.001$) than those associated with falls (270 ± 63 deg/s) (Fig. 3b). Peak trunk flexion angles and velocities on the sound side limb, all classified as recoveries, were measured to be $44 \pm 10°$ and 192 ± 46 deg/s, respectively, and were both significantly higher ($p < 0.001$) from those associated with recovery results on the prosthetic limb. The trunk flexion angle time series following three randomly delivered perturbations revealed a repeatable pattern (Fig. 4). RMS error of trunk flexion for all subjects ranged from 0.9° to 9.5° (mean $3.0 \pm 2.5°$ for sound limb, and $2.3 \pm 1.6°$ for prosthetic limb) (Fig. 5a). RMS error of trunk flexion velocity for all subjects ranged from 8.9 to 46.6 deg/s (mean 20.4 ± 10.1 deg/s for sound limb, and 23.2 ± 10.9 deg/s for prosthetic limb) (Fig. 5b). All RMS error calculations were performed for recovery trials only.

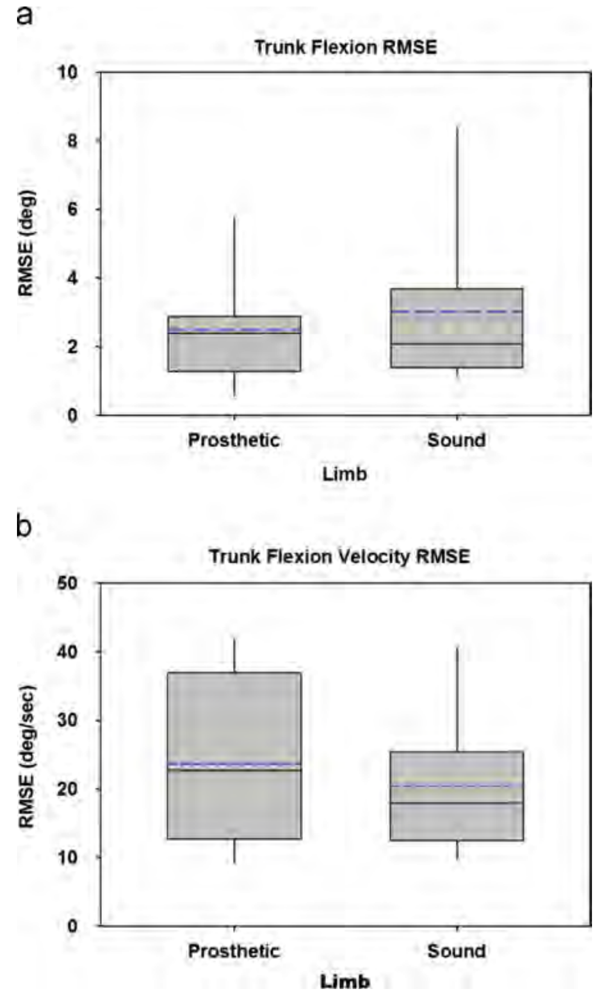

Fig. 5. Root mean square (RMS) error for (a) trunk flexion angle and (b) trunk flexion velocity between prosthetic and sound limb perturbation. The limb on the ground (stance limb) during the treadmill perturbation is described as the perturbed limb. Mean value is indicated by dashed line. The central line represents the median, the edges of the box are the 25th and 75th percentiles, and the whiskers extend to ± 2.7 standard deviations.

4. Discussion

This study reports a new method for repeatedly and reliably creating a postural disturbance during gait in a laboratory setting by using an instrumented treadmill. The ability to evoke a trip-like response at a specified time in the gait cycle in a clinical or laboratory setting has potential utility as a tool to assess trip-related fall risk and as a training tool to reduce fall risk. Results from this study were similar to those observed by Owings et al. (2001) who used a treadmill to deliver a large perturbation to initially standing subjects. Grabiner et al. (2012) showed this treadmill perturbation method was useful for decreasing the number of falls following a laboratory-induced trip in women. However, from the standpoint of neuromechanics, the considerable differences between initially standing and walking conditions prior to perturbation, suggests that even greater task specificity (i.e., fall-prevention training) may be achievable from the latter. There is some preliminary evidence that the use of treadmills to deliver perturbations during locomotion may reduce falls by older adults (Protas et al., 2005; Shimada et al., 2004). The present work indicates that controlled perturbations sufficient to cause subjects to fall unless an appropriate compensatory stepping response is performed can be delivered during locomotion using a treadmill.

Because of its size, cost, and complexity, the CAREN system used in our study is not a widely accessible technology. However, we think that the fundamental method described here could be implemented using most instrumented treadmills capable of large accelerations and rapid response. The clinical value of the virtual environment for this type of assessment/training is not known. However, using the incorporated CAREN technology for this study enabled recording of kinematic measurements of the perturbation response.

A limitation of most treadmill perturbations to simulate a trip is that, generally, it is not possible to replicate the sensory and motor conditions that arise when the swing phase of gait is obstructed by an external obstacle. However, the treadmill perturbations do create an overall pattern of whole body motion that is similar to what occurs following an actual trip. Consequently, we think that the increased use of instrumented treadmills in laboratory and clinical settings and ease of implementation can make this method of inducing a trip-like response an optimal method for measuring trip-recovery motor control while walking. Relatively low RMS error values for trunk flexion angle and velocity show the repeatability of the method within a subject. These values can be used for calculating sample size to determine significant differences when this method is used to assess an intervention. The larger fall rate observed during the initial perturbation for each subject indicates a precedent fall, with a majority of the subjects able to make adaptations to recover in subsequent perturbations, similar to that observed by Owings et al. (2001). It is recommended that data from second or third trips be used to determine subject performance. The ability to provoke repeated trip-like responses in a deliberate but random fashion gives researchers increased flexibility in testing the ability to recover from a potential fall.

5. Conclusion

Overall, the results demonstrate the feasibility of using treadmill-delivered perturbations during gait to reasonably simulate the conditions associated with recovery from an overground trip. These capabilities have the potential to assess trip-related fall risk and to be used as a training tool to reduce fall risk.

Conflict of interest statement

University of Illinois Chicago owns a patent on some of the technology used in the ActiveStep™ system, consequently there may be an institutional conflict of interest. Mark D. Grabiner is an inventor of the ActiveStep™ system but has no conflicts of interest to declare with regard to the present study.

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References

Alexander, R.M., 1989. Optimization and gaits in the locomotion of vertebrates. Physiol. Rev. 69, 1199–1227.

Blumentritt, S., Schmalz, T., Jarasch, R., 2009. The safety of c-leg: biomechanical tests. J. Prosthet. Orthot. 21, 2–15.

Brady, R.A., Pavol, M.J., Owings, T.M., Grabiner, M.D., 2000. Foot displacement but not velocity predicts the outcome of a slip induced in young subjects while walking. J. Biomech. 33, 803–808.

Centers for Disease Control and Prevention, 2013. Web-based Injury Statistics Query and Reporting System (WISQARS). National Center for Injury Prevention and Control, Centers for Disease Control and Prevention. Available from: ⟨http://www.cdc.gov/injury/wisqars/index.html⟩ (Online).

Eng, J., Winter, D.A., Patla, A.E., 1994. Strategies for recovery from a trip in early and late swing during human walking. Exp. Brain Res. 102, 339–349.

Grabiner, M.D., Bareither, M.L., Gatts, S., Marone, J., Troy, K.L., 2012. Task-specific training reduces trip-related fall risk in women. Med. Sci. Sports Exercise 44, 2410–2414.

Hof, A.L., Gazendam, M.G., Sinke, W.E., 2005. The condition for dynamic stability. J. Biomech. 38, 1–8.

Kadaba, M.P., Ramakrishnan, H.K., Wootten, M.E., 1990. Measurement of lower extremity kinematics during level walking. J. Orthop. Res. 8, 383–392.

Krasovsky, T., Banina, M.C., Hacmon, R., Feldman, A.G., Lamontagne, A., Levin, M.F., 2012. Stability of gait and interlimb coordination in older adults. J. Neurophysiol. 107, 2560–2569.

Miller, W.C., Speechley, M., Deathe, B., 2001. The prevalence and risk factors of falling and fear of falling among lower extremity amputees. Arch. Phys. Med. Rehabil. 82, 1031–1037.

Owings, T.M., Pavol, M.J., Grabiner, M.D., 2001. Mechanisms of failed recovery following postural perturbations on a motorized treadmill mimic those associated with an actual forward trip. Clin. Biomech. 16, 813–819.

Pavol, M.J., Owings, T.M., Foley, K.T., Grabiner, M.D., 1999. The sex and age of older adults influence the outcome of induced trips. J. Gerontol.: Biol. Sci. Med. Sci. 54A, M103–M108.

Pijnappels, M., Bobbert, M.F., van Dieen, J.H., 2004. Contribution of the support limb in control of angular momentum after tripping. J. Biomech. 37, 1811–1818.

Protas, E.J., Mitchell, K., Williams, A., Qureshy, H., Carolina, K., Lai, E.C., 2005. Gait and step training to reduce falls in Parkinson's disease. NeuroRehabilitation 20, 183–190.

Schillings, A.M., Van Wezel, B.M., Duysens, J., 1996. Mechanically induced stumbling during human treadmill walking. J. Neurosci. Methods 67, 11–17.

Shimada, H., Obuchi, S., Furuna, T., Suzuki, T., 2004. New intervention program for preventing falls among frail elderly people: the effects of perturbed walking exercise using a bilateral separated treadmill. Am. J. Phys. Med. Rehabil. 83, 493–499.

Smeesters, C., Hayes, W.C., McMahon, T., 2001. Disturbance type and gait speed affect fall direction and impact location. J. Biomech. 34, 309–317.

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14. ABSTRACT

Because trip-related falls account for a significant proportion of falls by patients with amputations and older adults, the ability to repeatedly and reliably simulate a trip or evoke a trip response in a laboratory setting has potential utility as a tool to assess trip-related fall risk and as a training tool to reduce fall risk. This paper describes a treadmill-based method for delivering postural perturbations during locomotion to evoke a tripping response and serve as a surrogate for an overground trip. Subjects walked at a normalized velocity in a Computer Assisted Rehabilitation Environment (CAREN). During single-limb stance, the treadmill belt speed was rapidly changed, thereby requiring the subject to perform a compensatory stepping response to avoid falling. Peak trunk flexion angle and peak trunk flexion velocity during the initial compensatory step following the perturbation were smaller for responses associated with recoveries compared with those associated with falls. These key fall prediction variables were consistent with the outcomes observed for laboratory-induced trips of older adults. This perturbation technique also demonstrated that this method of repeated, but randomly delivered, perturbations can evoke consistent, within-subject responses.

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